Design and Development of a Three Dimensional Compound Parabolic Concentrator and Study of Optical and Thermal Performance

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***Abstract*-Flat plate collectors have been widely used for applications that demand temperature below 90ºC and large amount of research efforts are already made. For medium temperature range (90–300ºC) applications, concentrating type collectors are suitable, which are under investigation. Despite such advantages, only limited studies are made. Almost all the 3-D CPC reported are fabricated using vertical segments which have more surface errors. Thus, they need precise techniques for fabrication. The 3-D CPC is fabricated with a new technique as horizontal segments, instead of vertical segments reported in the literature. Such horizontal segments are found to reduce the surface errors, so the optical efficiency is increased and hence the thermal efficiency is also increased. The optical efficiency has been estimated theoretically and compared with the experimental value. Experimentally determined values of optical and thermal efficiency is in good agreement with theoretically predicted values are reported. An attempt was made to generate low pressure steam using 3-D CPC in the in situ steam generation mode. The efficiency of the steam generation was about 38 %, which was one of the possible applications of 3-D CPC module**.

Keywords-3-D CPC; CPC; Optical Performance of CPC; Thermal Performance of CPC; Energy Efficiency

I. INTRODUCTION

The first design of CPC was described by Winston [1] in 1974. The design and construction details are reported in [2, 3]. The major advantages of 2-D CPC are that, it can receive radiation arriving with large angular spread and yet concentrate it on to linear receivers of small transverse width. The effect of mirror errors and receiver misalignments of the 2-D CPC were discussed by Rabl [4]. The varieties of 2-D CPCs in terms of their general characteristics, such as concentration, acceptance angle, sensitivity to mirror errors, size of the reflector area and average number of reflections are compared by Rabl [5].A 3-D CPC has been found to offer higher concentration over a 2-D CPC and the possible extension of 2-D CPC to 3-D CPC is reported by Rabl [6]. The 3-D CPC is designed [7-9] to concentrate homogeneous radiation incident within a fixed cone of direction on its entrance aperture. However the 3-D CPC is not an ideal concentrator in the sense that it does not transmit all available radiation within the nominal acceptance range to the exit aperture and therefore does not reach the thermodynamic limit for concentration. Indeed, the performance of the 3-D CPC can be improved [10] by slight variation in its shape. The classical three-dimensional compound parabolic concentrator (3-D CPC), a body of revolution formed by rotating the two-dimensional CPC (2-D CPC) around its axis, is often used in tandem with primary solar concentrators for augmenting the solar flux intensity incident onto solar receivers are explained by Lipinski et. al [11]. 3-D CPC composed of either plane facets or facets with one-dimensional curvature, which can be manufactured easily [12, 13]. This arrangement can be efficiently utilized by the use of concentrators with polygonal entrance apertures, which allow for placing concentrators built from simple facets side by side without gaps [14, 15]. The design of a practical 3-D CPC is a compromise among performance, ease of manufacture and cost. Thus, the overall dimensions and the number of reflections must be kept at a minimum and the shape of the device should be as simple as possible. The present work is focused to design and develop a new type of 3-D CPC modules to overcome the limitations of 2-D CPC. i.e to enhance the optical and thermal performances. The major objectives are:

- Design and fabricate 3-D CPC modules (two modules) for a half acceptance angle 4º to achieve higher concentration ratio. Two types of absorber coating materials were used for 3-D CPC modules. One with a commercially available ordinary black paint (refers as 3-D CPC IA) and another with Black Nickel –Tin selective coating (refers as 3-D CPC IB).
- To study the optical and thermal performances of the 3-D CPC modules and to investigate the performance of 3-D CPC modules as low pressure steam generator.

II. DESIGN AND FABRICATION

The reflector profile is designed and fabricated for a half acceptance angle 4° and a spherical copper absorber of radius (r) is 100 mm. For obtaining the profile of the parabola the following equations proposed by Rabl [5] are used.

$$x = r\sin\theta - \rho\cos\theta \tag{1}$$

$$y = -r\cos\theta - \rho\sin\theta \tag{2}$$

Where, $\rho = r\,\theta$ for $\theta \le \theta_1$

$\rho = (\theta + \theta_a + \pi/2 - (\cos(\theta - \theta_a))) / (1 - \sin(\theta - \theta_a))$

for $\theta_1 < \theta \le \theta_2$ and $\theta_1 = \theta_a + \pi/2$; $\theta_2 = 3\pi/2 - \theta_a$

For $\theta_a = 4°$, $\theta_1 = 94°$ and $\theta_2 = 266°$, by taking the value of $\theta = 0°$ to 266°, in the intervals of 10°, the values of x and y are calculated using equations (1) and (2). Using the values of x and y, a smooth curve is drawn (which gives the right half of the parabola) as shown in Fig.1. The mirror image gives the left half, that result in two-dimensional view of the 3-D CPC. Rabl [11] pointed out that top portion of reflector area can be truncated without significantly reducing the concentration. Based on this, 69 % of the top portion of the reflector is truncated and only 31 % is taken for construction. The truncated reflector profile (31%) is divided into seven equal segments as described by Hamadto and Warreen [16, 17]. To convert 2-D CPC geometry into 3-D CPC geometry a new methodology is used namely, approximate development method. The final shape of the reflector profile segments is

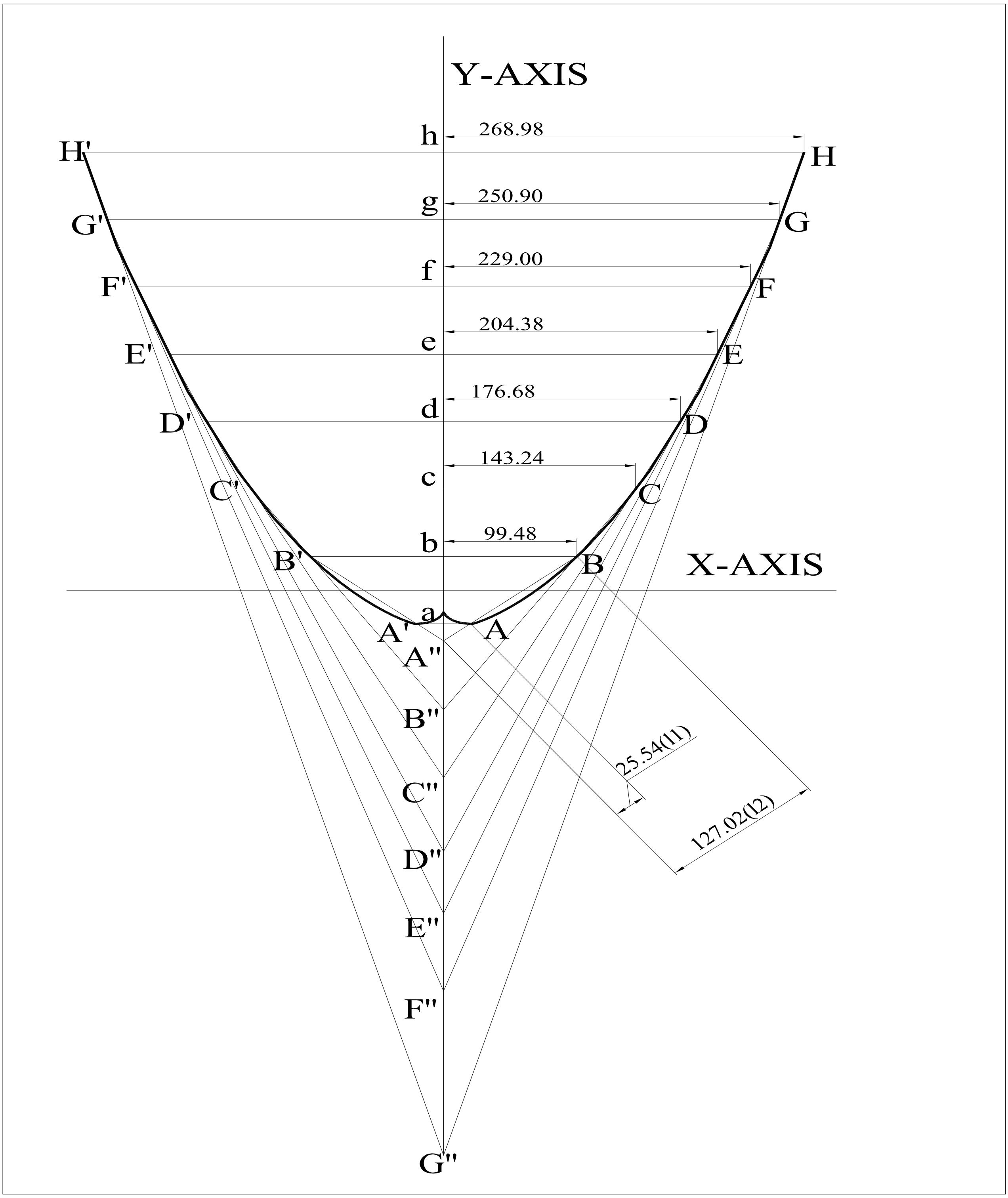

Fig. 1 Cross sectional view of 3-D CPC (Lengths are measured in mm).

shown in Fig.2.The paper templates are pasted on the metal sheet and then each segment of the reflector profile are individually fabricated and joined together. The UV stabilized aluminized polyester foil with reflectivity 0.85 is pasted over the metal sheet. The top of the reflector was covered with 3mm thick transparent glass of transmittance 0.90.

III. EXPERIMENTAL SETUP

To study the actual performance of the newly fabricated 3-D CPC, an experimental set-up was developed. The 3-D CPC module was fitted with fluid loop and water was used as heat transfer fluid as shown in Fig.3. Since the half acceptance angle of this 3-D CPC is 4° it needs tracking at an interval of 32 minutes (intermediate tracking). The inlet, outlet and ambient temperatures were measured using RTDs and an 8-channel data logger DAS 8000. The RTD (PT100), measures the temperature in the range of - 50 to 100°C. Pyrheliometer was used to measure the beam component of solar radiation. The flow rate of the fluid was measured using a graduated jar and a stopwatch. To provide a constant flow of water, a constant head tank was employed with an online heater to vary the inlet temperature. A wind velocity meter was also

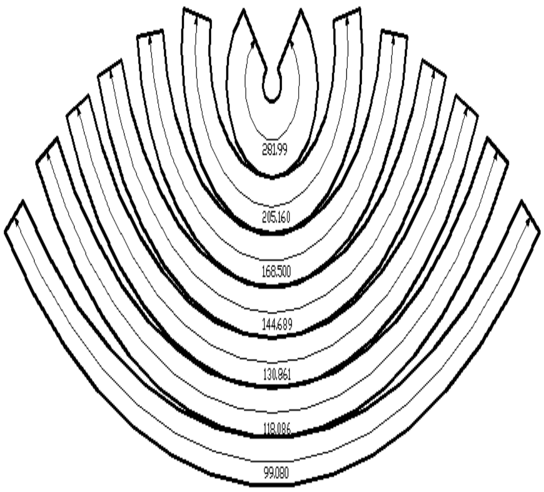

Fig. 2 View of reflector profile segments of 3-D CPC (Cutting angle ϕ in°)

Fig. 3 Experimental set up

used to find the wind velocity. The performance of the 3-D CPC modules were studied using the said experimental set-up in Erode city (11°02′N 77°03′E), Tamilnadu, India during representative clear sky days of summer season. The performance of the 3-D CPC mainly to estimate as optical efficiency, thermal efficiency and its capability to generate steam as discussed below.

IV. OPTICAL PERFORMANCE

Optical performance of two 3-D CPC modules was studied theoretically and experimentally.

A. Theoretical Estimation of Optical Efficiency

Optical efficiency is theoretically estimated from the optical parameters of materials used in the 3-D CPC construction. The optical efficiency of CPC with top glass cover and glass around the absorber [18] is given as

$$\eta_o = \tau_a \tau_e \rho_m^{<n>} \alpha P f_{ref} \quad (3)$$

The receiver thermal losses of 3–D CPC are primarily radiactive. As its absorber area is small, the absorber does not require the convection suppressing cover [19]. The average number of reflections (1.4) was calculated from [7] for a half acceptance angle 4º. Based on this, necessary modifications were made in the expression equation (3) for various CPC modules are given in the following Table I along with the estimated values of optical efficiencies.

TableI THEORETICAL ESTIMATION OF OPTICAL EFFICIENCY (η_o)

S.No	Module	Absorber Coating	Expression For η_o	Estimated Value Of Optical Efficiency
1	3-D CPC IA* without glass cover	Black paint	$\rho_m^{<n>} \alpha$	0.71
2	3-D CPC IA* with glass cover	Black paint	$\tau_a \rho_m^{<n>} \alpha$	0.645
3	3-D CPC IB* without glass cover	Black Nickel – Tin	$\rho_m^{<n>} \alpha$	0.732
4	3-D CPC IB* with glass cover	Black Nickel – Tin	$\tau_a \rho_m^{<n>} \alpha$	0.659
5	3-D Elliptical–hyperboloid concentrator [22] (Simulation work using Mat lab code)	-	-	0.78

*Note: τ_a = 0.90; ρ_m = 0.85 ; <n> = 1.4 ; α = 0.90

B. Experimental Determination of Optical Efficiency

To determine the optical efficiency by experimentation, the method described by Rabl and Balasubramanian [20] and [21] was used. Based on this, the optical efficiency was computed as,

$$\eta_o = (m° C_w (T_o – T_i) / I_b A) \quad (4)$$

Where, m° is the mass flow rate of fluid, C_w is the specific heat capacity of water, T_o is the outlet temperature, T_i is the inlet temperature, A is the aperture area and I_b is the beam component of solar radiation. The experiments were carried out on a number of clear sunny days. The optical efficiencies of two 3-D CPCs were experimentally determined and are shown in Table Ⅱ. The other way of determining the optical efficiency is from instantaneous efficiency curve (Fig. 4 and Fig. 5) are discussed in section V.*A*

C. Results and Discussion

From Table.1, the estimated optical efficiency of a 3-D Elliptical–hyperboloid concentrator by simulation work [22] is in good agreement with 3-D CPC IA & 3-D CPC IB. From Table.2, the theoretically estimated optical efficiency values are in good agreement with experimental optical efficiency values. Further, the optical efficiency values of 3-D CPC IB are higher than that for 3-D CPC IA due to the selective coating given to that absorber. Also, it clearly shows that, the experimentally determined optical efficiency values of 3-D CPCs are higher than the 2-D CPC values reported earlier. Thus, the newly fabricated 3-D CPC module has a better optical performance than 2-D CPCs reported earlier [23, 24]

V. THERMAL PERFORMANCE

The performance of CPC has been calculated in terms of instantaneous efficiency and heat loss co-efficient. The instantaneous efficiency of the CPC is given as [18]

$$\eta_i = F' [\eta_0 – U_L (T_{av} – T_a)] / I_b \quad (5)$$

For better functioning of a collector at higher temperature with a reasonably high efficiency, the overall heat loss coefficient ($F'U_L$) should be made as low as possible.

This $F'U_L$ could be determined in two ways: i) From the slope of the instantaneous efficiency curve; ii) From thermal loss rate at zero solar irradiance. The experimental determination of instantaneous efficiency of 3-D CPC

modules at different inlet temperatures were calculated and discussed below.

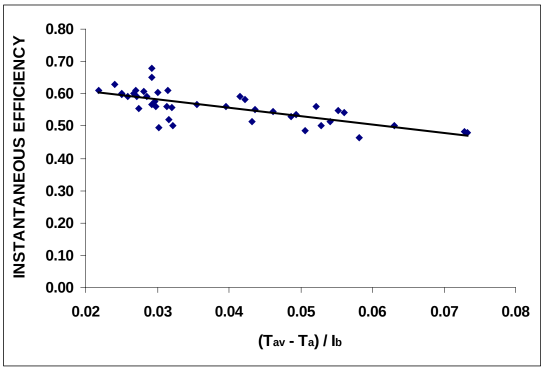

Fig. 4 Instantaneous efficiency curve of 3-D CPC IA

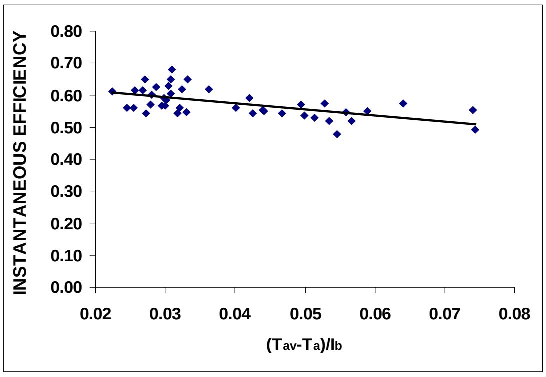

Fig. 5 Instantaneous efficiency curve of 3-D CPC IB

A. Overall Collector Efficiency

The collector was incorporated in the fluid loop and operated in the closed loop mode for its performance study at different operating temperatures. The closed loop mode involves sump, pump, on line heaters etc., the complete experimental set up for 3-D CPC is shown in Fig 3. To start with, a higher inlet temperature of 40°C was maintained with the help of online heater arrangement. The experiments were carried out only on clear sunny days. The inlet, outlet, ambient temperatures, and pyrheliometer readings were recorded for every two minutes. Steady state conditions were obtained only around noon time. These values were used for computing the overall efficiency of the collector [18] as,

$$\eta_i = m°C_w (T_o - T_i) / I_b A \qquad (6)$$

The experiment was repeated for a number of days for the same inlet operating temperature 40°C to check the repeatability. The experiments were conducted for various operating inlet temperatures, viz 50°C, 60°C, 70°C and 80°C. The graphs (Fig.4 & Fig.5) were drawn between instantaneous efficiency (η_i) and $\Delta T / I_b$, where $\Delta T = [T_{av} - T_a]$ and I_b is the beam radiation. The optical efficiencies of 3-D CPC modules were also calculated from the Y – intercepts of Fig.4 & Fig.5 ($F'\eta_0$, 0.622 for 3-D CPC IA and 0.634 for 3-D CPC IB respectively). Also the slope of the curves gives the heat loss coefficient ($F'U_L$, 3.16 W/m^2°C for 3-D CPC IA and 2.85 W/m^2°C for 3-D CPC IB respectively). Hence the two 3-D CPC modules were investigated, the thermal performance of 3-D CPC IB was found to be better than 3-D CPC IA both in terms of optical efficiency and heat loss coefficient.

B. Determination Of Heat Loss Coefficient F'UL

The other method to determine the heat loss coefficient ($F'U_L$) is thermal loss rate determination during night time. The useful heat collected by CPC under steady state condition is given as [18],

$$A_c F' U_L (T_{av} - T_a) = m° C_w (T_i - T_o) \qquad (7)$$

From steady state values of m°, T_o and T_i, the loss rate $A_c F'U_L (T_{av} - T_a)$ was calculated using equation (7). These values are plotted against ($T_{av} - T_a$). The experiment was conducted for various inlet temperature and necessary measurements were recorded. The calculated values of F'UL for 3-D CPC modules are 3.27 W/m^2°C for 3-D CPC IA and 2.76 W/m^2°C for 3-D CPC IB respectively.

C. Results And Discussion

Table III gives the experimentally determined values of heat loss co-efficient ($F'U_L$). The heat loss coefficient of 3-D CPC modules are comparatively lower than 2-D CPC modules reported earlier [22, 23].

V. IN SITU STEAM GENERATION WITH CPC MODULES

To utilize the benefit of 3-D CPC in real time applications, it can be used as low pressure steam generators. To create an experimental set-up for steam generation test, the fabricated 3-D CPCs absorber assemblies were slightly modified (condenser unit attached at the outlet of the absorber) to generate low-pressure steam. Both the inlet and the outlet ends of the absorber were connected to a borosilicate glass flask of nearly 2.5 liter capacity acting as a water reservoir.

TableII OPTICAL EFFICIENCIES OF VARIOUS CPCS (η_o)

S.No	Module	Absorber Coating Type	Theoretical Estimation Of η_o	Experimental Values η_o
1	3-D CPC IA	Black paint	0.645	0.626
2	3-D CPC IB	Black Nickel-Tin	0.659	0.638

TableIII COMPARISON OF HEAT LOSS COEFFICIENT (F'UL)

S.No	Module	By Instantaneous Efficiency Method (W/M^2 °C)	By Thermal Loss Rate Method (W/M^2 °C)
1	3-D CPC IA	3.16	3.27
2	3-D CPC IB	2.85	2.76

A. Steam Generation Test

Steam generation tests were carried out with 3-D CPC IA and 3-D CPC IB on clear sky days. The instantaneous efficiency for steam generation (η_i) was compiled from the relation [18],

$$\eta_i = m L / I_b A t \qquad (8)$$

The average steam generation instantaneous efficiency for the whole day was calculated, taking into account the total quantity of steam generated, were nearly 37 % for 3-D CPC IA and 39 % for 3-D CPC IB. The corresponding values for the sheet and foil type CPC, acrylic mirror 2-D CPC are 32 % and 19 % [22].

VI. SUMMARY AND CONCLUSIONS

Two 3-D CPC modules for a half acceptance angle 4° was designed and fabricated by using a new methodology. With the half acceptance angle 4°, the operation of the collector at temperature higher than 100° C was justified by getting good energy collection efficiencies. This is the main advantage of the 3-D CPCs.

The methodology adopted in the design and fabrication of 3-D CPC modules has the main advantage that it could be easily mass produced. The overall approach for the design and construction of the 3-D CPC module appears to be good as indicated by the good agreement between the theoretically estimated and experimentally measured values of optical efficiencies.

Experimentally determined values of optical efficiency of 3-D CPC IA and 3-D CPC IB are in good agreement with theoretically estimated values and also in good agreement with 3-DE lliptical–hyperboloid concentrator. The optical efficiency values of 3-D CPC IB are higher than 3-D CPC IA due to the selective coating given to the absorber. And also it is clear that the experimentally determined optical efficiency values of 3-D CPCs are higher than the 2-D CPC values reported earlier.

From the instantaneous efficiency studies of the 3-D CPC module at different operating temperatures, it has been found that the efficiency of the 3-D CPC modules is fairly high even at higher operating temperatures. Performance studies beyond 70^0C could not be made due to the practical difficulties in maintaining steady flow rate which may be due to the formation of water vapor bubbles at higher temperature.

From the overall collector efficiency study, the thermal performance of 3-D CPC IA and 3-D CPC IB were observed, the performance of 3-D CPC IB (high optical efficiency and low thermal loss co-efficient when compared with 3-D CPC IA) was found to be better than 3-D CPC IA. The lower the thermal loss co-efficient may be due to selective coating to the absorber, for which the radiative contribution is quite small.

The experimentally determined values of thermal loss coefficient are in good agreement with earlier reported values for 2-D CPCs of less or same concentration. But this experimental value is found to be higher in few cases, which may be due to somewhat higher air infiltration rate in the annulus space between the absorber without glass envelope. Anyhow it requires some further investigation experimentally and refinement of thermal modeling.

The average steam generation efficiency values were also quite good when compared with the 2-D CPC values reported earlier. Steam generation tests reveal that the use of 3-D CPC IB which reduces the water holding capacity decreases the warm-up time. The cumulative collection of steam condensate was found to be more in 3-D CPC IB. This may be due to selective coating to the absorber.

Other possible applications of 3-D CPC powered solar steam generator are generation of electric power and sterilization process. At the time when attention is firmly focused worldwide on control and prevention of pollution, efficient use of energy and more reliance on renewable energy sources, this low pressure solar steam generator is a welcome addition to fight against environmental pollution and it is packed with energy saving and environmental friendly features.

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